EXPLORATION OF THE ORIGINS OF VERY HIGH STRENGTHS IN NANOLAYERED MATERIALS

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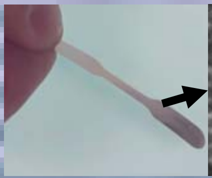
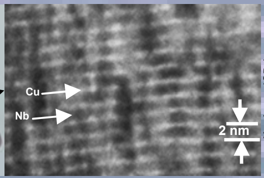
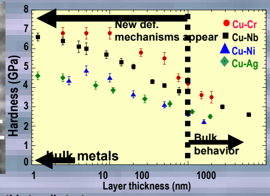
Research supported by DOE, Office of Science, Office of Basic Energy Sciences

Atom-by-atom deposition of different metals into alternating nanometer scale layers creates a new realm of composites with extraordinarily high levels of strength and toughness. Using a synergistic set of approaches involving synthesis, nanomechanical testing, microscopy, crystal plasticity, and atomistic modeling, our team is exploring a variety of new concepts in the physics of strengthening nm-scale materials. *Nano-scale design of layered metals shows promise of synthesizing the strongest metals ever known.*

Layered Metallic Composites Develop Remarkably High Strengths as Layer Thickness Approaches Nanometer Dimensions





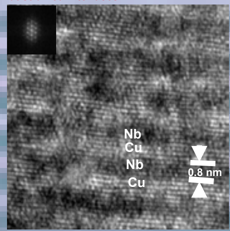


- Physical vapor deposition (evaporation or magnetron sputtering) is used to synthesize this tensile test specimen that contains thousands of nm-thick alternating Cu and Nb layers shown in the TEM micrograph.

- Nanoindentation hardness measurements show that nanolayered metallic composites are more than 1000 times stronger than the individual constituents in bulk forms, with peak strengths within a factor of 2 to 3 of the theoretical strength limit. Nanolayered metals deform differently from bulk metals revealing many new deformation mechanisms underlying their unusual behavior.

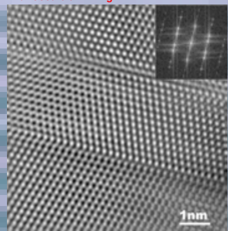
Electron Microscopy Reveals Unusual Structures near Interfaces

New atomic arrangements are stabilized at strained interfaces



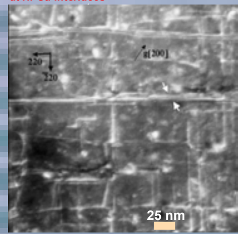
High-resolution TEM image of 0.8 nm Cu / 0.8 nm Nb multilayers and corresponding <111> zone axis diffraction pattern show that Cu adopts a bcc structure, different from its fcc structure in bulk form.

Nanoscale twinning



High-resolution TEM image showing nanoscale {111} twinning in the Cu layer of Cu/stainless steel multilayer. Even finer scale twinning is observed in stainless steel layers. MD simulations show that nanoscale twin interfaces are strong barriers to slip.

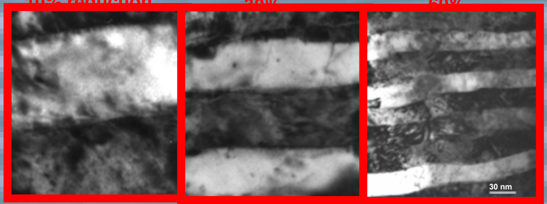
Complex Dislocation Structure form at Ni-Cu Interfaces



Plan View TEM image showing cross-grid of misfit dislocations on a (001) interface in a 10 nm Ni / 100 nm Cu bilayer. Arrows show stacking faults in the Ni over layer, consistent with MD simulation predictions shown below, but otherwise unexpected in bulk materials.

Nanolayered Metals are Surprisingly Stable During Mechanical Working and Develop Unusual Deformation Textures

10% reduction 30% 60%

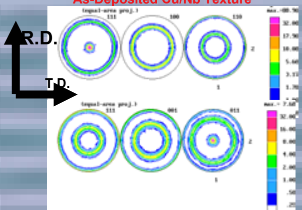


Progressive reduction in layer thickness with rolling

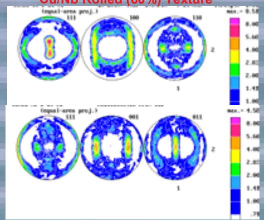
Bulk Materials:
Inhomogeneous deformation

Nanostructured Materials:
Homogenous deformation

As-Deposited Cu/Nb Texture



Cu/Nb Rolled (60%) Texture



- Both metals undergo uniform reduction in layer thickness to strains as high as 60%
- No dislocation cell structure formation during rolling, in sharp contrast to bulk metals
- New deformation textures: *no lattice rotation occurs during rolling in sharp contrast to monolithic materials*
- Rolling further enhances the hardness

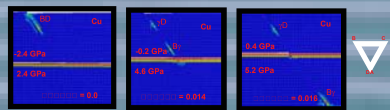
Atomistic Models Reveal Critical Features of Deformation near Interfaces

In nanometer-scale metallic composites, plasticity is controlled by single dislocation transmission across interfaces. MD simulations reveal two ways of tailoring interfaces to obtain unusually high strengths:

Systems with large coherency stresses (e.g., Cu/Ni)

1. Slip planes and directions continuous across interfaces.
2. In a coherent Cu/Ni bilayer, an edge partial dislocation crosses the interface when the coherency stresses are overcome.

Response of Coherent {001} Cu-Ni interfaces to in-plane tensile stresses

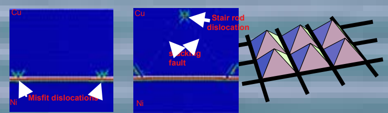


Dislocation BD is strongly repelled from the interface by the coherency stresses in the Cu

As the applied strain is increased, BD splits into two partials as it approaches the interface.

At an applied stress of 2.4 GPa the leading partial crosses the interface and glides off into the Ni. The stress in the Cu is slightly positive. The stress in the Ni is huge.

Response of semi-coherent Cu-Ni interfaces to in-plane tensile stresses



At zero applied stress interface dislocations are nearly collapsed.

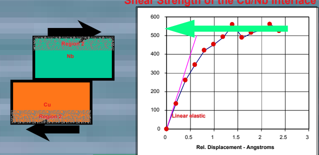
Tensile stress causes interface dislocations to dissociate into partials that react to form stairrod dislocations

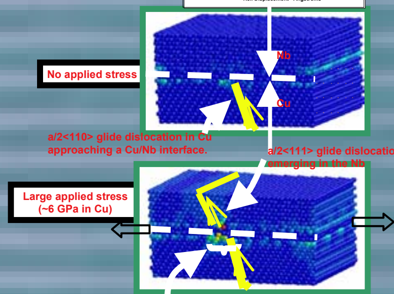
Under applied stress, misfit dislocations may dissociate into partials gliding on intersecting planes. These can react forming stairrod “locks”. In 3-D, the interface structure develops into an array of pyramids consisting of defects known as stair-rods and stacking faults. The computer models also indicate that this structure is very resistant to deformation.

Systems with relatively weak interfaces (e.g., Cu/Nb)

1. Slip planes and slip directions change at the interface.
2. The interface can shear.
3. Glide dislocations from one layer enter the interface and spread making it difficult for them to transmit slip into the adjacent layer.

Shear Strength of the Cu/Nb Interface





a/2<110> glide dislocation in Cu approaching a Cu/Nb interface.

a/2<111> glide dislocation emerging in the Nb

a/2<110> glide dislocation from the Cu has entered the Cu/Nb interface and its core has spread.